University of Glasgow
DEPARTMENT OF
AEROSPACE ENGINEERING

Recent developments in the 3' x 3' flow visualization wind tunnel

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R.B. Green
Department of Aerospace Engineering
University of Glasgow
Glasgow
G12 8QQ

Summary

This report presents a description of the modifications to the Aerospace Department's "Smoke tunnel" that took place over the summer of 1997. These improvements were essential for research developments taking place. Also described are essential items of user information regarding programming, safety and use of the equipment.

Contents

1. Introduction

In the early 1990s a small wind tunnel of a design similar to that described by Head & Bandyopadyay [1] was built in the basement area of the James Watt (South) building. The wind tunnel is of the non-return type, and a diagram is shown in figure 1.

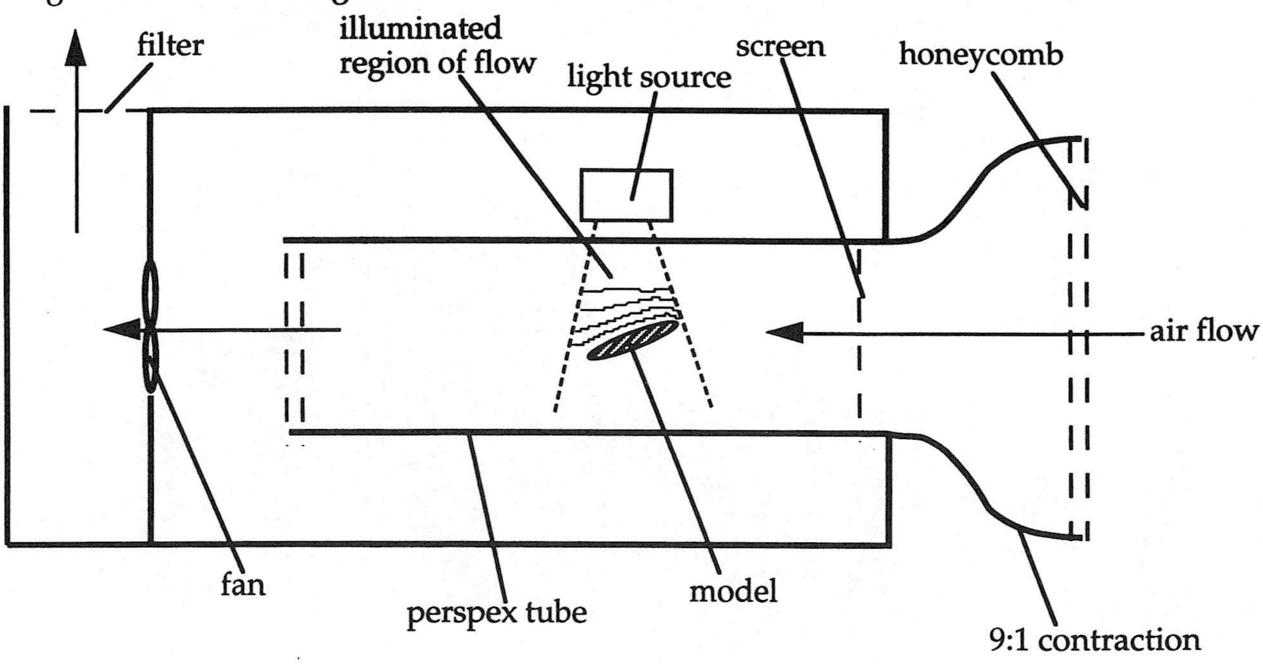


Figure 1 Schematic diagram of smoke flow visualization wind tunnel

The working section is housed inside a sealed room. A fan is placed at the downstream end of the working section, so that when the fan runs air is sucked through the 9:1 contraction and down the working section. The air then passes into another sealed room and back out into the atmosphere through filters. The working speed is approximately $1ms^{-1}$ and the wind tunnel is suitable for qualitative flow visualization investigations of separated flows and turbulence.

The majority of work in the tunnel to date has been for unsteady aerodynamics to assist with investigations taking place in the larger

[1]Head, M.R. & Bandyopadhyay, P. (1981) J. Fluid Mech., **107**, pp 297-338

departmental facilities. Instrumentation has been in the form of actuation equipment, computing equipment, video and wet-film based imaging and an Argon ion laser for illumination. Actuation has been achieved using low cost stepper motors from RS components; these offer ease of programming with a reasonable amount of power for unsteady model motion. Their operation has often been poor, however, due to electrical noise and vibration, and scant attention to construction quality of the various rigs over the years has compounded the problems, and has led to poor reliability. Computing facilities have dated quickly; the originally purchased Macintosh LCIII has poor processing power and no further expansion bays for additional data acquisition equipment or communications cards to the University network. There has therefore been significant motivation to upgrade these particular items. The video based imaging equipment has proved to be a useful tool, and this has been relied upon in preference to traditional photographic techniques. Efforts have been made over the past year, however, to get a working PIV system, which necessitates resurrection of the Department's photographic capabilities. Difficulty of adjustment of the laser light sheet optics have high-lighted the need for improvements to this part of the system; remote adjustment is essential, so that the user can see the desired effect without risk of direct exposure to the laser beam. In conjunction with the effort to get a working PIV system, improvements to the laser system have also been necessary. In particular the laser available is not of sufficient power. Finally the long working section of the wind tunnel requires a slider/ trolley system so that relevant instrumentation can be moved along the length of the tunnel. The rails originally installed onto the top of the wind tunnel were of a quality barely sufficient for supporting equipment, let alone allowing easy movement. Therefore, this was also an area for attention.

The performance of the above instrumentation was beginning to compromise the success and quality of any projects taking place within the smoke tunnel. Therefore, with a view to carrying out specific research projects and to upgrade the facility a number of equipment grant applications were made. These were to a scheme for new lecturers from the Nuffield Foundation, and to the Dunlop Chapman and John Robertson bequests from the University of Glasgow. A total of £35000 of funding was obtained, and this report contains a description of how it was allocated and how the upgrades were implemented.

2. Details of upgrade to facility

It is convenient to initially report the upgrades in the context of the awarding bodies; this is essentially due to the nature of the research tasks to be performed.

2.1 Provision of facilities from the Nuffield Foundation

The grant applied for from the Nuffield Foundation was essentially for a flow visualization and PIV study of unsteady delta wing flows. To assist with these studies the actuation system needed to be upgraded, and funds were applied for for this purpose. In addition for the PIV studies a hexagonal mirror was to be purchased. A full amount of £3600 was applied for although less than this was awarded. The mirror was eventually purchased from another source. Purchase of the actuation system was shared with another grant; the motor was also used to position a vortex generator for the BVI studies project underway at the Spencer St. facility. This sharing of resources allowed a higher specification motor than originally planned to be bought. The motor was a Panasonic digital AC servo motor with 750W of power. Its nominal torque was 3Nm, although peak torques of 7Nm were possible. The maximum rotational speed is 3000 rpm which allows substantial gearing. The motor has a 2500 ppr optical encoder on its shaft for digital feedback, and the unit itself is of a compact size. To allow programming of the motor a PC was purchased (150MHz Cyrix CPU, 32MB RAM, 1.2GB hard drive and ethernet card). For control of the motor a data acquisition card was purchased from the BVI studies budget. This card was a National Instruments Lab-PC+, which has 8 12-bit analogue input lines, 3 8-bit digital input/ output ports, three programmable counters and two 12-bit analogue output lines. The analogue output lines are especially useful since they may be programmed as waveform generators. Remaining funds from the Nuffield Foundation were then used for construction of two wind tunnel models, the purchase of other items for construction of the actuation rig, optics for laser illumination and photographic consumables.

2.2 Provision of facilities from the John Robertson Bequest

In conjunction with the research projects on unsteady aerodynamics, the smoke tunnel is useful for the study of turbulence. This requires the whole length of the tunnel to be used. Therefore funds for the improvement of the rail/ trolley system were applied for from the John Robertson (JR) bequest of the University of Glasgow. The items applied for were high quality beam sliders and materials for the construction of the trolley, and a servo motor for contrl of the position of the trolley. Substantially less was awarded than was applied for. With Departmental assistance, therefore, the rails and trolley were obtained. Funds from the JR bequest paid for one 5m long beam slider system from Hepco Ltd. This beam consists of a long aluminium extrusion with a diamond shaped slider bolted to one of its sides. One carriage plate was also purchased from the JR funds. Departmental funds paid for the other beam and three carriage plates. The carriage plates support the trolley and permit smooth motion of the trolley along the beam.

A schematic of the slider/ trolley system is shown in figure 2.

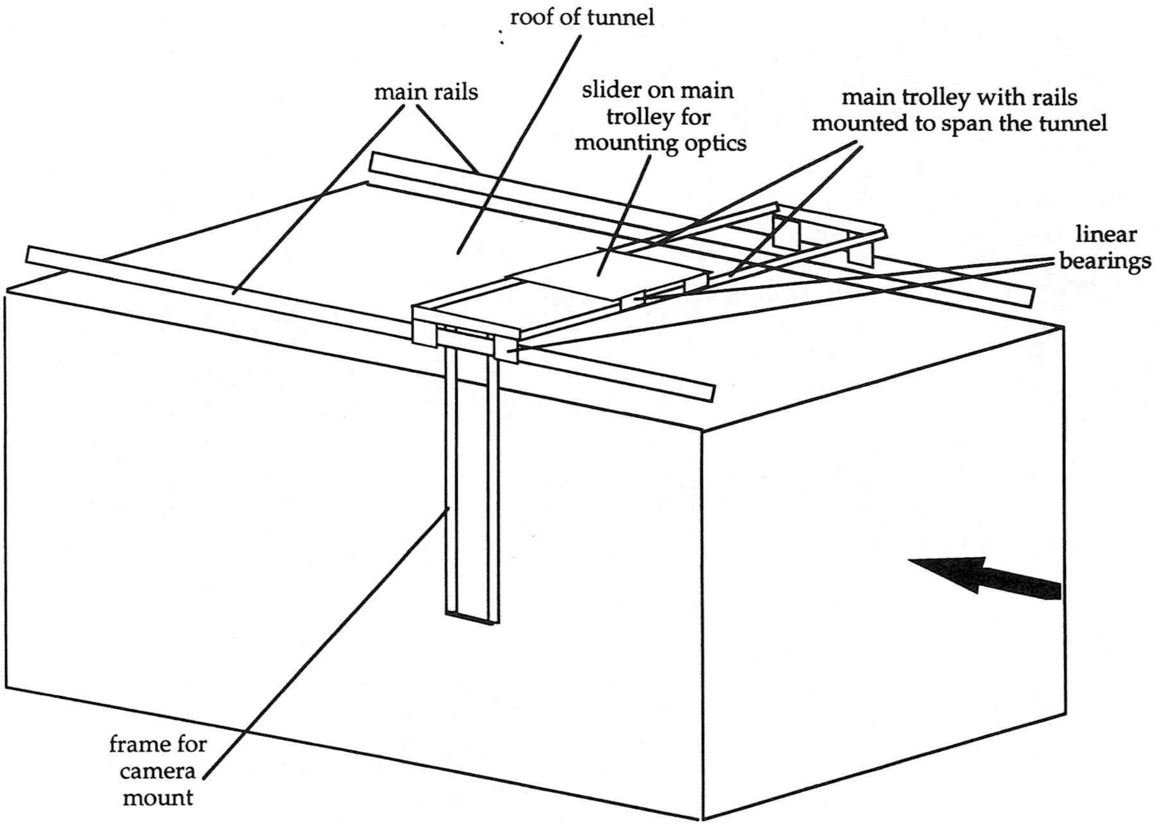


Figure 2 Schematic of rail/ trolley system

The beams were hung from gantries suspended from the wind tunnel room framework such that the rails themselves were on the underside of the beams; this means that vibration caused by motion of the trolley is isolated from the wind tunnel itself. The trolley projected over the viewing side of the wind tunnel so that camera systems may be mounted on the trolley. The trolley itself was constructed of a 19mm thick wooden plate, with a carriage plate fixed on each corner. A wide slot spanning the width of the wind tunnel was cut out of the trolley, and this slot permitted laser illumination of the flows from above the wind tunnel. To permit easy movement of the laser optics a ball screw/ slider system was mounted parallel to the slot so that the optics could move across the entire wind tunnel. The ball screw was powered by a small stepper motor, and the cylindrical lens to create a light sheet from the laser beam was also rotated by stepper motor. This set up permitted remote positioning of the laser illumination as originally required. The optics and motors were purchased from a variety of sources including the JR bequest and the Nuffield Foundation. The original design of the system was to have the Argon laser mounted in a fixed position at the end of the wind tunnel. It was decided, however, to mount the laser on the trolley itself. This arrangement caused some problems (trolley weight and laser cooling), but also significantly reduced the optical path lengths for the Argon laser,

therefore reducing beam divergence. A schematic of the trolley is shown in figure 3.

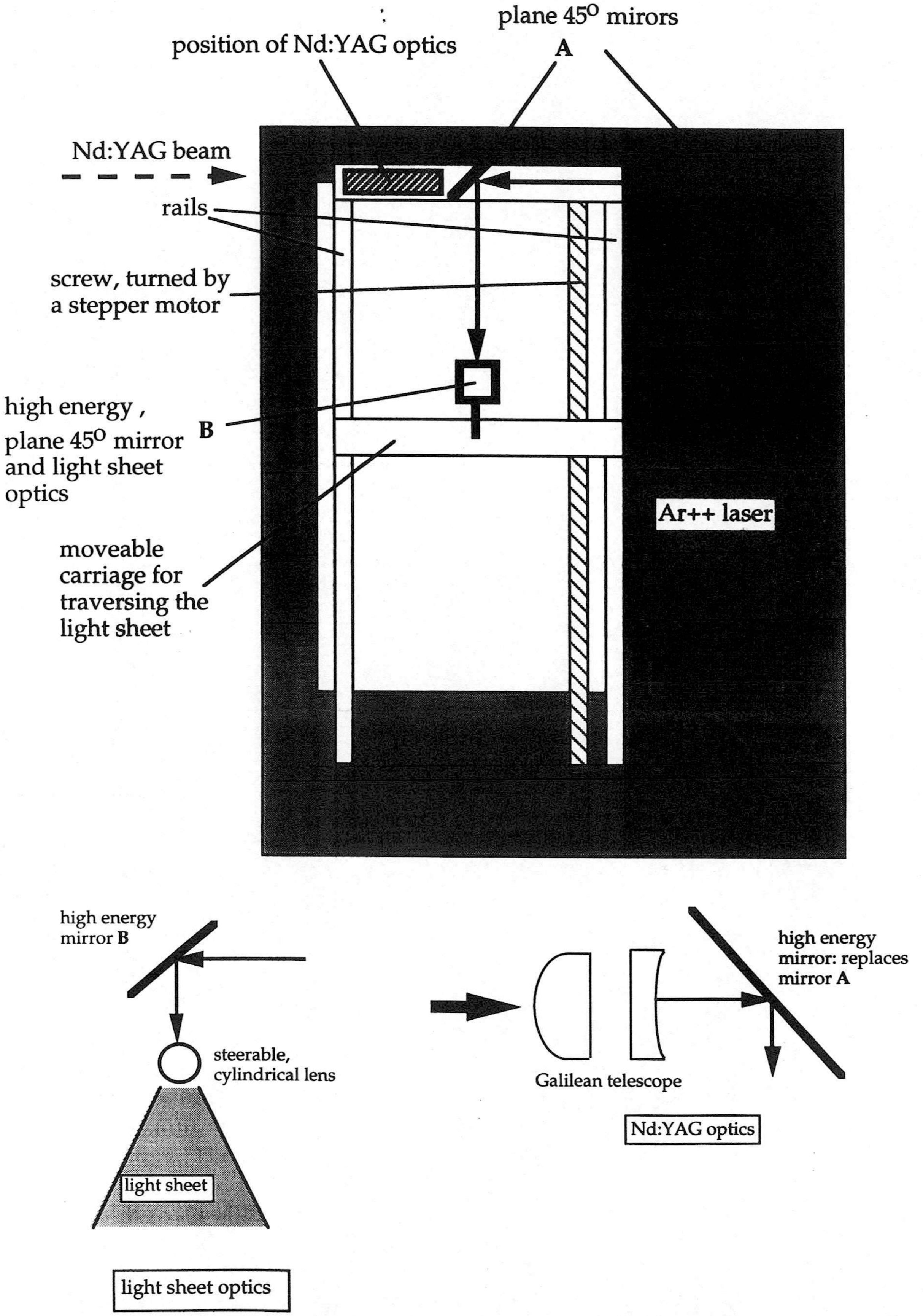


Figure 3 Schematic of trolley for carrying Argon laser and optics for creation of light sheet for Argon and Nd:YAG lasers. Note the positions of the lens surfaces for the Galilean telescope for the Nd:YAG laser

2.3 Provision of facilities from the Dunlop Chapman bequest

Particle Image Velocimetry (PIV) is a powerful tool for the fluid dynamicist. The principle is straightforward in that the motions of small particles suspended in the flow field are photographed. In this way an almost instantaneous measurement of the fluid velocity at many points over a wide area can be taken. The Department has relied upon expertise and equipment from other establishments for PIV work in the past, and the lack of its own equipment has stifled some projects. The view of the author is that PIV is an essential technique that all Departments with an interest in fluid mechanics should have access to, and it was with this in mind that money was applied for from the Dunlop Chapman bequest, so that PIV could be used to support current research projects. The original application was for an argon ion based system, with scanners, software, computers and cameras included in the bid. It emerged that the argon ion system would not offer great value for money, so instead a double-pulsed Nd:YAG laser from Spectra Physics was purchased. The model is a GCR-130-10 with second harmonic generator and double-pulse option installed. The repetition rate is 10Hz. In single pulse mode the output pulse has an energy of 250mJ in the green (532 nm).

The above laser has been integrated into the smoke tunnel laboratory. It is positioned upon a shelf built over the end of the working section. The green output port shines onto the optic system mounted on the above described trolley (the optics are shown in the trolley schematic on figure 3). Safety issues are described later.

3. Implementation of upgrades

Implementation of the upgrades takes place mechanically, electronically and by programming for the specific experiment. Integration of the YAG laser with the facility was also an important task.

3.1 Mechanical implementation

The major mechanical work to implement the upgraded items was in the form of positioning and aligning the rails and fixing the servo motor to the actuation rig.

3.1.1 Positioning and alignment of rails

The rails were bolted onto the gantries hanging from the wind tunnel roof. Alignment of the rails then proceeded as follows:

(i) One rail was levelled with a spirit level.

(ii) A set square was used to check the alignment of the rail with the tunnel side (in the absence of a machined surface for reference this is accurate enough).

(iii) A small diode laser was mounted on a carriage plate and slid along the rail. The laser beam was pointed at the far wall of the tunnel. The carriage plate was moved at regular intervals (e.g. 20cm) along the slider, and the position of the laser beam noted at each point. Any bending in the slider is made clear by the locus of the projected laser beam onto the far wall of the tunnel. If the movement of the laser beam is the same for each carriage plate position then the rail is straight. If any bending is apparent then the rail is adjusted as necessary.

(iv) The rail was bolted tight and the above checks were made again.

(v) The second rail was aligned with the first by firstly levelling it and adjusting it to the same height as the first rail. This was achieved using spirit levels. The rail was then made parallel to the first by moving the whole trolley up and down the rails and adjusting the yaw of the second rail to achieve consistently smooth motion along the whole of the length of the rails. The support bolts for the second rail were then tightened, and the diode laser was then positioned on the trolley and the alignment of the whole system checked as per (iii).

The above process takes approximately two days.

The main difficulty is the lack of concrete reference points; the rails are effectively aligned with the tunnel side and and set to be horizontal.

3.1.2 Mechanical implementation of servo motor

The main piece of equipment that the motor was to be used to drive was the screw shaft/ flange nut assembly for pitching 3-D models. This is simply a vertically mounted, 40mm per rev screw. As the screw rotates the flange nut on the screw shaft is constrained to move vertically by a linear bearing and shaft assembly mounted parallel to the screw shaft. The flange nut is connected to the model via suitable likages. The previous system used pulleys and belts to connect the motor to the screw shaft, although for the upgrade a direct coupling was used. The coupling was a size 70, HRC type motor coupling, which consists of two cast iron flanges which mesh together through a stiff rubber pad. The flanges are fixed to the motor and screw shafts using Taper Lock bushes.

To further improve model motion, the attachment from the flange nut to the model was stiffened by passing the actuation rods through high quality linear bearings set into the floor of the tunnel. This prevents unwanted sideways motion of the actuation rods at the floor of the tunnel, thereby stiffening the whole arrangement. A schematic of the new arrangement is shown in figure 4.

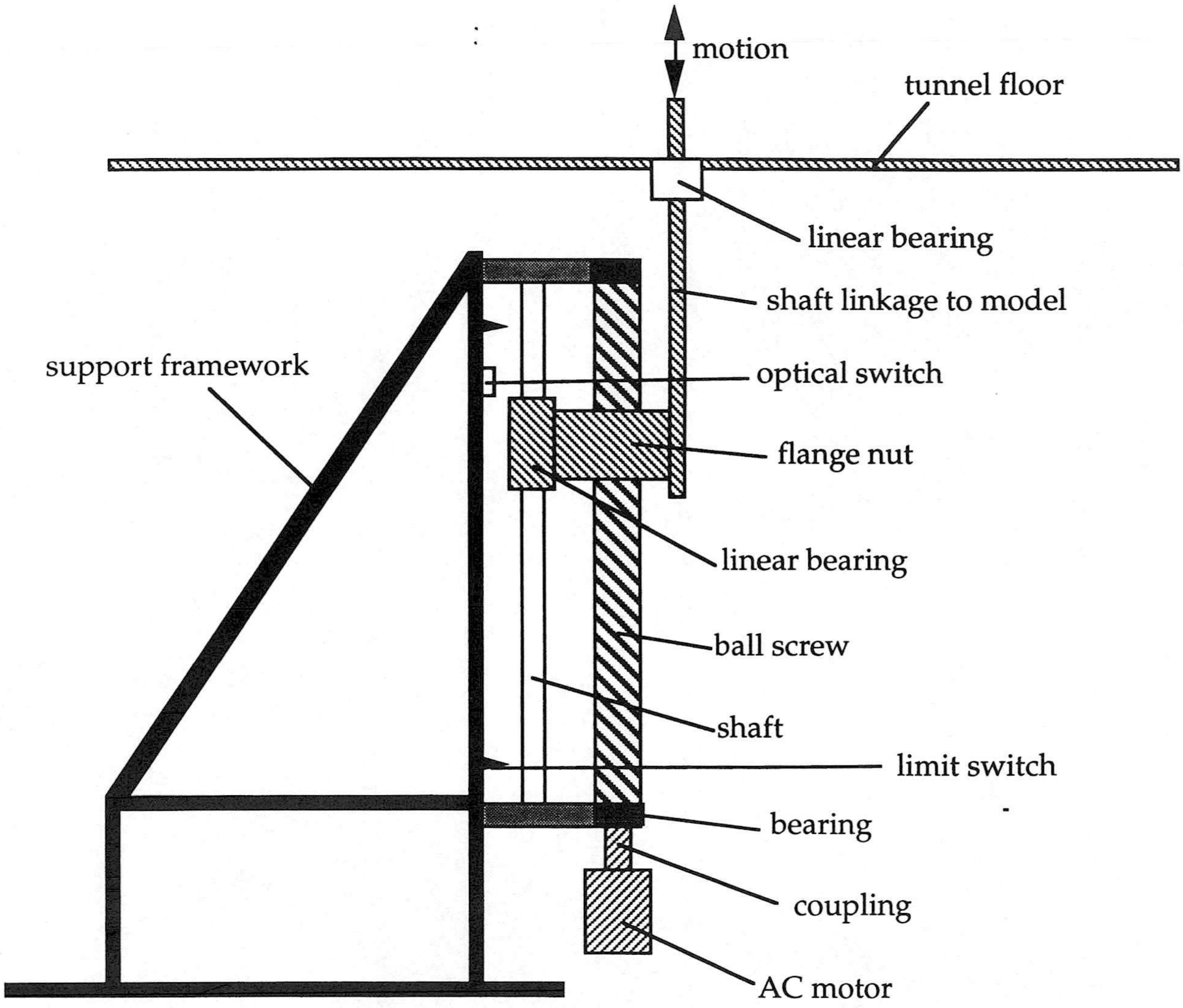


Figure 4 Schematic of model actuation apparatus

3.2 Electronic implementation of the servo motor

To function safely in the correct manner the servo motor control connections must be wired in a specific manner. These control connections are either open or closed circuits from the relevant wire of the control interface to ground, and the wires are accessible through a 37 way D-type interface. The pin numbers corresponding to these wires are given in the motor users manual, but for convenience are given below:

Function	pin number	Action to effect function
servo on	12	connect to ground for on

clockwise motion inhibit	29	connect to ground
anti-clockwise motion inhibit	30	connect to ground
zero-speed cramp	10	open circuit
speed control	14 15	apply proportional voltage ground
speed feedback	16 17	voltage proportional to speed ground

Servo on can be applied at any time. The inhibit signals instantly prevent motor motion in the specified direction; these connections are wired to micro-switches at the extreme ends of the screw motion to prevent over-running of the screw. The speed control voltage is supplied by the computer. Monitoring of the speed feedback signal is not necessary except for motion analysis purposes. For the control circuitry to work correctly a 24V d.c. supply to pin 11 is necessary. Pin 28 is the main ground connection.

In addition to the above necessary connections through the D plug, settings must be made through the key pad on the servo motor control panel. These must be set as follows:

parameter	**function**	**setting value**
02	control mode	1 (speed control)
13	gain setting	35 (depends upon desired motor speed at 6V speed command input value. See later.)
16	speed command	0 (sets speed command signal to external)
17	zero-speed cramp	0 (activate cramp input command)

Essential settings such as above should be burned onto the control unit's EEPROM, and instructions for this are given in the instruction manual.

Note that the user manual must be consulted before the motor is set up for any new application.

3.3 Programming the servo motor

The method of programming the servo motor depends strongly upon the application that it is to be used for. For the present unsteady aerodynamics

applications its main function is to provide rapid pitching of the wind tunnel model. The motor has three basic control modes: position control, velocity control and torque control. Position control uses input pulses to rotate the motor shaft by discrete amounts, while velocity and torque control uses analogue voltages at the relevant control wire to produce the desired effect. The present dynamic application suggests that velocity control is the most appropriate option; torque control requires detailed knowledge of the inertia of the system, while position control is best suited for low speed applications. The control mode chosen has to be input to the servo motor controller through the keypad as described above.

The present section now describes the method for generating the analogue control voltage for the motor. Historically unsteady aerodynamics of pitching wings has been investigated through constant pitch rate (ramp) or sinusoidally varying pitch rate motions. For the ramp motions the important parameters are the start and finish incidence and the pitch rate. For the oscillatory motions the important parameters are the mean pitch angle, the amplitude and the frequency. Programming therefore involves a clear way of inputting the data, determining the output control waveform and the generation of the wave form. The chosen programming language was LabVIEW v3.0; this language provides facilities for easy construction of a user interface, and communication with hardware is straightforward. Currently available expertise could also be exploited.

3.3.1 Input of run parameters

This programming task essentially deals with the design of the user interface so that the function of the data to be entered is clear to the user. Errors should be trapped so that impossible model motions are not generated.

The first task is the setting of the run type; these are ramp-up, ramp-down and oscillatory. Then, depending upon the run type, the user should be prompted for the start incidence and finish incidence or mean incidence and amplitude as appropriate. Ramp rate or pitching frequency are then required. If any run parameter exceeds pre-determined maximum values or do not make sense then the user is prompted to re-enter the data.

Separate virtual instruments (vi's) were written to input the relevant parameters, the final output from the input control vi being the run type and relevant angle of incidence and velocity/ frequency information. The basic form of each vi is that of a while loop containing the input and check information. A switch is pressed to end the while loop once the user is satisfied that the entered data are correct. Hard copies of LabVIEW programs are impractical to present, so a suitable algorithm for an input vi is presented below in pseudo code form:

```
flag = FALSE
```

```
DO
        {
        ENTER value

        IF (value > maxvalue OR value < minvalue) THEN
                flag = TRUE
        ELSE
                flag = FALSE
        }
WHILE (flag =TRUE)
```

Note that a list of LabVIEW vi's and their function is given in section 3.6.

3.3.2 Calculation of control voltage

The control voltage is analogous to the desired motor speed, since the feedback encoder is mounted on the motor shaft. Therefore the transfer function between the motor shaft rotation and the model rotation about its quarter chord point needs to be determined (this is not necessary if an encoder is mounted on the model pitch axis). This transfer function is a straight forward geometric exercise. The model geometry is shown in the figure below.

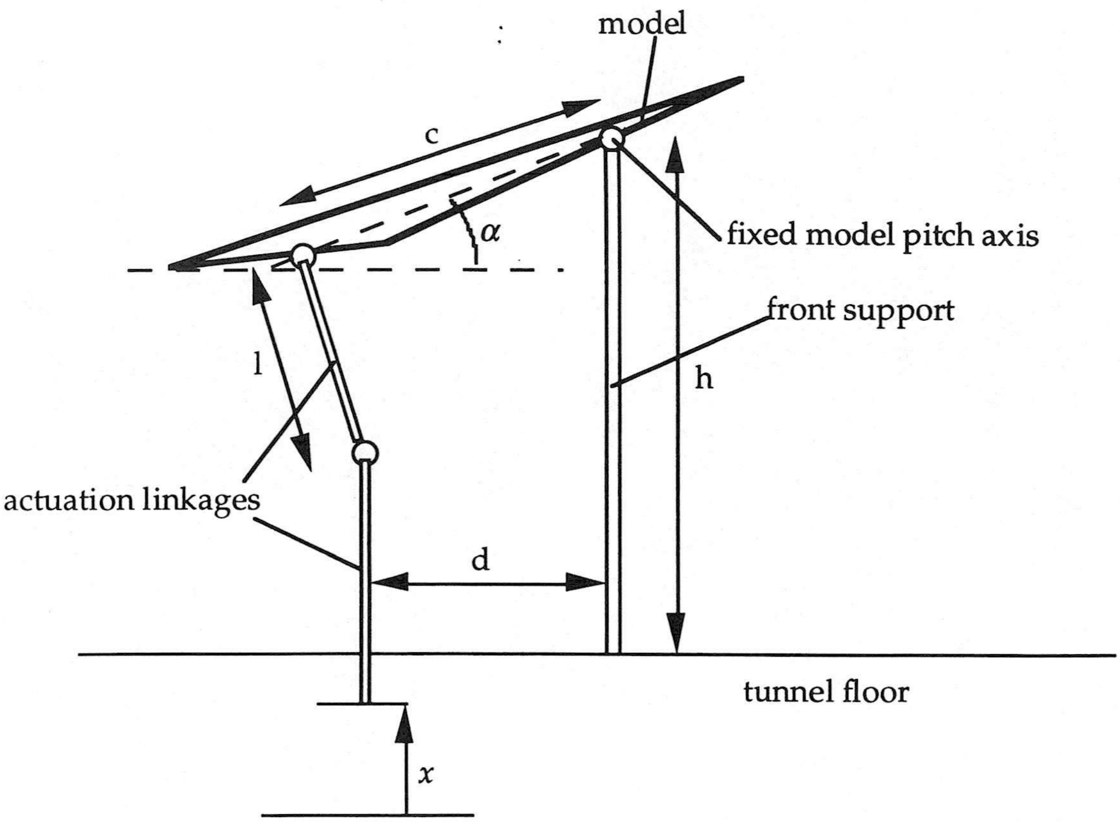


Figure 5 Model geometry for derivation of transfer function between model incidence α and flange nut motion x

For this geometry and notation, the flange nut motion x is related to the model incidence α by the expression

$$x = h - c\sin\alpha - \sqrt{l^2 - (c\cos\alpha - d)^2}$$

and therefore the flange nut velocity $\dot{x}$ is related to model incidence α and pitch rate $\dot{\alpha}$ by the expression

$$\dot{x} = -c\dot{\alpha}\cos\alpha - \frac{c\dot{\alpha}(c\cos\alpha - d)\sin\alpha}{\sqrt{l^2 - (c\cos\alpha - d)^2}}$$

Flange nut velocity is directly proportional to shaft rotational velocity, the constant of proportionality for which is dependent upon the screw pitch (40mm per rev in the present case). In turn shaft rotational velocity is directly proportional to the applied voltage. This constant of proportionality is user specified; the maximum input voltage is 6V (although the waveform generator has a maximum output of 5V), and the rotational speed required at 6V has to be specified by the parameter 13, described earlier. *The value entered into the servo controller and the value used in the calculation of the control voltage must be compatible or*

severe damage to the servo motor., model and linkages may result. If the settings are changed at all, then attention must be payed to the servo motor instruction manual so that correct, compatible values are set.

The voltage v to produce the desired pitch rate $\dot{\alpha}$ is therefore given by

$$v = pk\left(-c\dot{\alpha}\cos\alpha - \frac{c\dot{\alpha}(c\cos\alpha - d)\sin\alpha}{\sqrt{l^2 - (c\cos\alpha - d)^2}} \right)$$

where p is the screw pitch *in revolutions per unit* nut movement and k is the number of volts *per revolution per second* that the servo motor controller is set for. As mentioned above, this setting is crucial.

For both ramp and oscillatory motions the model motion is discretized into 1050 equally spaced time points. Practical considerations mean that for ramp motions the model must accelerate gently from zero speed to the required ramp rate and vice versa. This is essential to prevent unwanted transients which would be the result of an attempt to impulsively start the model motion. The acceleration and deceleration take place over 5% of the pitch range in a sinusoidal fashion. The control voltage is then calculated for ramp and oscillatory motions as follows. Model incidence and pitch rate are calculated at each time point together with the corresponding flange nut velocity (the model and pitch mechanism geometry must be measured accurately, as they are input values for the transfer function). The correct voltage to produce the required pitch rate at each point is then calculated. The time duration of the run is calculated so that the rate at which the voltage values are fed to the waveform generator may be determined. The voltage values are then fed into an array.

3.4 Practical considerations for control of the motor

A number of items need to be considered before the actuation system can be used. These are safety considerations and the issue of fixing a datum point. The safety aspects are to ensure that the model cannot run to too high or too low an incidence, which may be the result of some failure of the system. This is achieved by mechanical micro-switches at the extreme ends of the model motion range, which are designed to activate the clockwise and counter clockwise inhibit if they are touched. When the system is started there is no way of knowing for sure what the model incidence is. There is therefore an unknown offset added to the required model displacement. This offset can be removed if some known reference point, or datum, is referred to. This may be done manually by the user or automatically by the computer; the latter approach is preferable. The datum used is in the form of an optical switch located at some fixed, known position. Provided the system is not adjusted or tampered with, then this position is fixed and represents a constant value. At the start of a series of tests, the idea is then for the computer to move the model slowly

to search for this datum; the datum has been found when the optical switch output state changes from high to low. This change of state is measured by a digital line on the data acquisition card. When the datum has been found the model incidence is known to a high accuracy. Provision for re-locating the datum whenever required should be provided, and experience with the stepper motors indicates that the datum should be located after each test.

In addition to unsteady aerodynamic testing, tests at fixed incidence are always required, and the option for this within the control code must be included. The movement from one incidence to another for a static test is most simply treated as a low pitch rate ramp test.

A pseudo code representation of the overall control code is as follows:

MAIN PROGRAM:

```
find_datum

DO
        {
        ENTER run_option
        IF (run_option = "static") perform_static_test
        IF(run_option = "dynamic") perform_dynamic_test
        IF(run_option = "datum") find_datum
        }
WHILE (run_option ≠ "quit")
```

FUNCTION find_datum:

```
read_switch_state

IF (switch_state = FALSE) THEN
        {
        decrease_pitch_angle_slowly
        read_switch_state
        WHILE(switch_state = FALSE)
                {
                read_switch_state
                }
        }
ENDIF

set_model_to_zero_degrees
```

FUNCTION perform_static_test:

```
find_datum
```

```
previous_incidence = 0
DO
        {
        INPUT continue
        IF (continue = TRUE) THEN
                {
                INPUT model_incidence
                IF (model_incidence > previous_incidence) THEN
                        test_type = "ramp-up"
                ELSE
                        test_type = "ramp_down"
                final_incidence = model_incidence
                start_incidence = previous_incidence
                ramp_velocity = 10
                calculate_voltage_array
                move_model
                previous_incidence = model_incidence
                }
        }
WHILE (continue = TRUE)
```

FUNCTION perform_dynamic_test:
note that this is the minimum to produce the desired effect

```
find_datum

DO
        {
        INPUT continue
        IF (continue = TRUE) THEN
                {
                input_test_parameters
                calculate_voltage_array
                IF (test_type = "oscillatory") THEN
                        start_alpha = mean_incidence + amplitude
                ELSE
                        start_alpha = start_incidence
                set_model_to_start_alpha
                wait_for_four_seconds
                IF (test_type = "oscillatory") THEN
                        {
                        move_model
                        DO
                                {
                                INPUT motion_continue
                                }
                        WHILE (motion_continue = TRUE)
                        stop_model
```

```
            ELSE
                  {
                  move_model
                  wait_for_four_seconds
                  }
            find_datum
            }
      }
WHILE (continue = TRUE)
```

Note: the function input_test_parameters returns the test type, start or mean incidence, finish incidence or amplitude and ramp velocity or frequency. These parameters are required by the calculate_voltage_array function

The function move_model must initially set the rate generator (counter 0) to the required value. Using externally timed waveform generation guarantees that the required rate of output is achieved. If internally timed waveform generation is used then the actual rate of output if data may be significantly different from that required. In addition with externally timed generation model motion may be started in response to some trigger. The voltage array is fed to the waveform set up v.i. and the motion is then started in either single waveform mode or continuous mode for oscillatory tests. The LabVIEW user manuals should be consulted for correct setting up for waveform generation.

LabVIEW listings are not included with this report, since, in the opinion of the author, they are difficult to read and not necessarily informative. However the complete versions of the code are found in the software archive for the smoke tunnel work.

Note that a list of LabVIEW vi's and their function is given in appendix 1.

3.5 Integration of Nd:YAG laser with smoke tunnel facilities

The YAG laser is to be used for illumination for flow visualization and PIV. In addition to the optical set up, an important task is for synchronization of the laser with the model motion.

3.5.1 Optical set up

The optical set up shares some components with the Argon laser (one mirror and the cylindical lens) although a Galilean telescope and another high energy mirror also need to be used. The optical set up is shown in figure 4. Great care must be taken to ensure that no focussed back reflections return to the YAG laser output aperture. This is essential to avoid severe damage to the YAG rod, Q-switch and Pockels cell. The

curved surfaces of the Galilean telescope must be set facing the correct directions (see figure 4), and all reflecting surfaces must be adjusted so that back reflections are aimed away from the laser output aperture. This can be observed safely at low laser energy. ***The YAG laser must not be adjusted without prior consultation of the user manual and the assistance of an experienced user.***

3.5.2 Synchronization of YAG laser with model motion and camera

The objective here is to pulse the YAG laser when the model reaches a specified incidence. The difficulty is that the laser is pumped by a flash lamp running continuously at 10Hz. Although the flash lamp must run continuously, a single laser pulse is possible; if the laser fire command is opetated, the laser actually fires at the next available flash lamp pulse. Earlier models than the GCR-130-10 could deliver a single flash lamp pulse; this facility has not been designed completely out of the GCR series lasers, although Spectra-Physics recommend that the flash lamp runs continuously.

Therefore in the present case, instead of the laser firing when the model reaches a specified incidence, the laser must fire at a specific time point, and this time point must coincide with a flash lamp pulse. The signal to fire the laser must arrive shortly before the specified time point for the actual laser pulse. The laser power supply has as an output a signal synchronous with the flash lamp firing. The leading edge of the pulse coincides with the start of the flash lamp energy envelope, and the pulse width is 0.5ms. This output signal was therefore used as the basis for synchronizing the model motion with the laser flash lamp. The algorithm for synchronization is as follows:

(i) determine the time after the start of the run at which the laser firing incidence is reached

(ii) determine the number of one-tenth second intervals (i.e. the number of whole one-tenths and the remainder) within this time delay

(iii) there must be a whole number of one-tenth second intervals between the start of the run and the laser firing incidence. Therefore the additional time required is determined (i.e. one-tenth minus the remainder calculated above).

(iv) the array containing the model velocity voltage information is padded out with the required number of zeroes (for zero speed) at the start of the run. The required number of zeroes is the additional time determined above times the waveform update rate.

(v) a second array is calculated which contains the laser firing information. This array is output through the second waveform generator on the LAB-PC+ data acquisition card. This waveform is responsible for

providing the actual signal for firing the laser, and the laser fire signal must arrive shortly before the desired flash lamp. Therefore this waveform undergoes a 0-5V transition at 1/20s before the laser firing incidence is reached.

The synchronization process is not complete. Owing to the synchronization method above the start of waveform generation coincides with a flash lamp signal; the flash lamp signal could therefore be used to trigger the start of the waveform generation. It is now essential the waveform is updated externally, since if it was updated internally then there would be no precise control of the start of the generation. In practice, therefore the run is started at the corect time as follows:

(i) counter 1 output is hard wired to counter 0 gate, counter 1 clock is wired to the flash lamp synch signal, and counter 0 output is wired to the EXTUPDATE pin on the LAB-PC+ terminal block.

(ii) counter 1 output is set low.

(iii) counter 0 is configured to provide the correct update rate.

(iv) counter 1 is then programmed to count down 10 pulses. In the LabVIEW code the waveform generator is loaded with the arrays after this point.

(v) on the tenth flash lamp pulse the output status of counter 1 goes high, which opens the gate for counter 0. Counter 0 output now begins pulsing at the required rate; waveform generation has now started at the required time to a good accuracy.

A further important consideration is synchronization of the camera shutter with the model motion. It is possible to open the camera shutter before the model motion starts. There are two problems associated with this. Firstly there is light leakage within the smoke tunnel, so as short an exposure as possible is preferable. Secondly the Argon laser is of the continuous wave type, so a short exposure is essential for a dynamic test. It is best, therefore, that the camera shutter opens when it is needed, and this was achieved as follows. There is always a delay between the camera fire signal and the shutter actually opening; using the Argon laser and a photodiode it was determined that this time delay is some 220 ms. Therefore the camera fire signal must be supplied accordingly. This fire signal is included on the waveform that fires the YAG laser itself. (There is a laser pulse associated with this, but the camera shutter at this point would be closed so it does not matter.) The signal to fire the laser is a low to high to low pulse of 5V amplitude and 20ms duration that closes a short circuit via a relay. The short circuit causes the camera shutter to open at the set shutter speed.

The overall synchronization sequence is shown in figure 6.

For static tests (i.e. where the model is not moving) the problem of synchronizing the camera shutter with the laser pulse becomes the problem. In this case, the waveform that controls the camera shutter and laser fire signals must be synchronized with the laser flash lamp signal. The shape of the control waveform is the same as that indicated in figure 6, since its overall function is still the same. As in the dynamic case the flash lamp signal may be fed to counter 1 to control the start of the control waveform generation; waveform generation is then effectively started by a specific flash lamp pulse. Since the laser flash lamp fires at 10Hz and the time between camera shutter open signal and the shutter actually opening is 220ms, then the camera open signal must come (80 - T/2)ms after the start of the waveform generation, where T is the shutter exposure time in ms. The part of the waveform that provides the signal to fire the laser must be set at not less than 210ms and not more than 290ms into the wave form. Note that as in the dynamic case two laser pulses are the result (since camera fire and laser fire are controlled by the same signal), but the first pulse may be ignored since the camera shutter will still be closed.

The above synchronization methods are easily incorporated into the LabVIEW code, and the hard wiring is straight forward. In practice the counters on the Lab-PC+ board are very sensitive to electrical noise, so care must be taken to reduce the noise. A wiring schematic is shown in figure 7, and the Lab-PC+ terminal block connections are listed below (refer to the Lab-PC+ user manual for a description):

terminal	**function**	**connection**
10	motor drive waveform (DAC 0)	motor speed control (pin 14 on the motor control box)
12	camera & laser control waveform (DAC 1)	to relay to fire camera
14	set zero speed cramp (PA0 (OUT))	to relay to set zero speed cramp (pin 10 on the motor control box)
22	read datum switch status (PB0 (IN))	to opto-switch output
39	update waveforms (EXTUPDATE)	to OUT B0
41	rate generator to update waveforms (OUT B0)	to EXTUPDATE
42	synchronization with YAG laser (GATEB0)	to OUTB1
43	synchronization with YAG laser (OUTB1)	to GATEB0
45	synchronization with YAG laser (CLKB1)	to YAG laser lamp sync output

Note that ground must be connected accordingly.

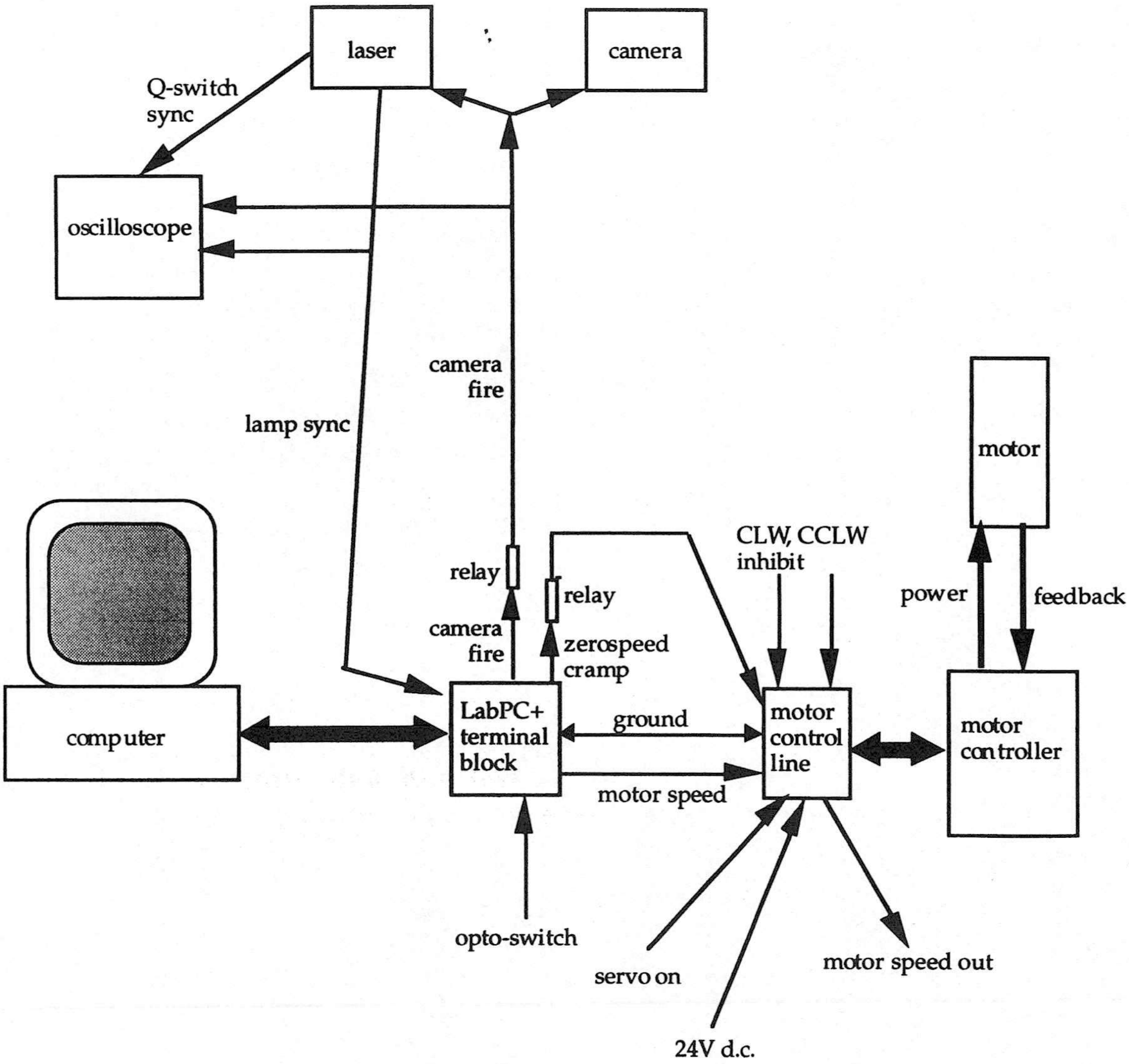
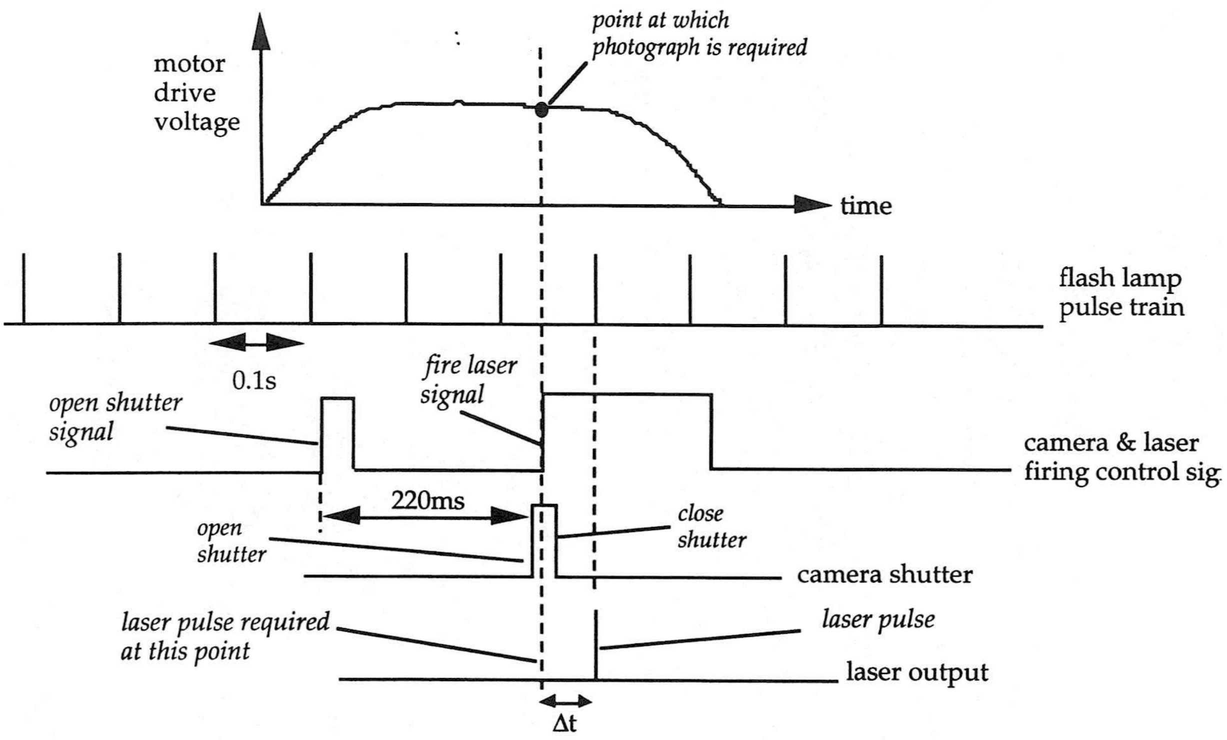
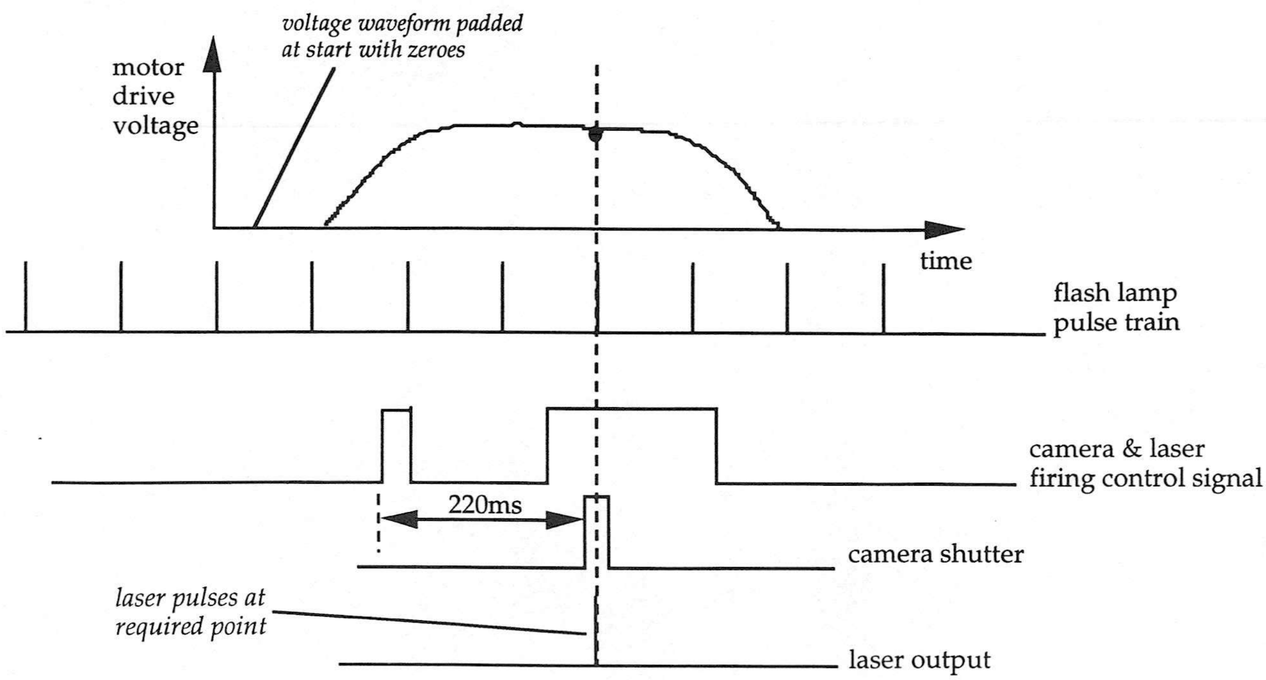


Figure 7 Wiring schematic for the synchronization of the laser, model motion and camera

Note that the only synchronization problem for the Argon laser is the camera shutter opening time. If photographs are required at times less than 220ms after the start of the model motion, however, the motor drive voltage signal still needs to be padded with zeroes at the start so that the shutter has time to open.



(a) unsynchronized laser pulse occurs Δt seconds after it is required. This time delay is unknown and is not fixed.



(b) laser pulse is synchronized with model motion by synchronizing drive voltage generation with flash lamp pulses and padding the start of the drive voltage signal with zeroes. Note laser fire signal comes before the desired flash lamp pulse.

Figure 6 Synchronization of Nd:YAG laser with model motion.

3.6 Nd:YAG laser safety

The Nd:YAG laser is capable of delivering a 250mJ, 10ns pulse of light at 532nm (green). In addition there is some output of infra-red radiation. Although the laser energy is modest, it is a class IV laser and is highly dangerous; inadvertent exposure can lead to blindness and other injuries. It is therefore essential that the laser radiation is completely enclosed such that there is *no* risk of exposure to the user. Since the wind tunnel has a perspex roof and side, these would have to be covered where necessary, and access to the laser head and optics would also need to be prevented. These precautions would require the installation of shields and interlocked doors. However, the easiest option in the short term is simply to move the computer for control of the experiment out of the wind tunnel and to interlock the tunnel doors.

4.0 Testing of the new actuation and laser system

4.1 Accuracy

A full test for fidelity of the actual model pitch rate compared to the desired pitch rate has not yet taken place fully; simple visual inspection of the input and output velocity waveforms on an oscilloscope has revealed a good comparison. A more complete analysis will take place via a final year project exercise. The model positioning accuracy during a static test is good (better than 0.5^{o}) and there is little accumulation of errors.

During dynamic testing with the laser pulsing, preliminary investigations showed that the laser firing was accurate (better than 0.01s or scope accuracy), so long as precautions to reduce electrical noise had been taken.

4.2 Reliability

A full shakedown test is essential so that pitfalls can be identified. The system is basically reliable and mechanically sound. Prior to a new test sequence the following tests must be performed:

(i) check operation of optical switch
(ii) check synchronization of laser and model motion

The first check may be made through the control program itself; finding the datum position includes a semi-automatic check on the operation of the optical switch. The second check has to be made using a digital storage oscilloscope. Checking the correct operation of the YAG laser during a static test is sufficient. All that needs to be known is whether the Q-switch sync pulse occurs the right amount of time after the open shutter signal (see figure 6); this should be 228ms. The digital oscilloscope should be set up with the laser/ camera fire as the trigger, and with triggering to occur on a leading edge transition. This test should be carried out a few times with the AC motor ON, since counter 1, which synchronizes the hardware,

may triggered by excessive noise which can de-synchronize the laser flash lamp with the rest of the equipment. If possible the same check should be made during an actual test sequence as well.

5. Conclusions

Extensive improvements to the Aerospace Engineering Department's Smoke Flow visualization wind tunnel have been made. These include improvements to the computing and data acquisition capability, inclusion of a high quality model actuation system, addition of a high power laser for flow visualization and PIV, enhancement of laser safety and completion of the overhead rail system. The relevant mechanical, electronic and software steps towards the full exploitation of the various items of equipment have been described.

APPENDIX 1: Details of LabVIEW vi's for control of AC motor and YAG laser

A list of LabVIEW vi's written for generating the model motion and firing the YAG laser is given below:

Static tests

static test.vi:

Performs a static test. This vi calls auto-home.vi, run-static.vi, static photo.vi

inputs: datum position (single precision).
outputs: none

run-static.vi

Moves model from one incidence to another. Sets pitch rate to $10^{o}s^{-1}$. Calls panel1.vi, panel2.vi and actuate.vi.

inputs: initial alpha, final alpha (both single precision).
outputs: none

static photo.vi

Opens camera shutter and fires YAG laser. Sets update rate as 1000Hz. This vi calls static synchro.vi. The YAG laser synchronization sequence is then invoked.

inputs: none
outputs: none

static synchro.vi

Generates array containing information for the firing sequence for the YAG laser for a static test. The array is written to D/A channel 1, and waveform generation is started in external update mode using the relevant DAQ vi calls.

inputs: none
outputs: fire sequence waveform (single precision array)

Dynamic tests

RUNTEST.vi

Performs dynamic test. This vi calls ptchyag.vi, setstart.vi, and actuate.vi.

inputs: datum (single precision)
outputs: none

ptchtag.vi

This vi inputs all the various run parameters from the user and calculates the drive arrays for the motor and the camera/ YAG laser. The vi calls panel1.vi, panel2.vi, panel3.vi, enable laser.vi, YAGFIRE.vi, firetime.vi, and synchro.vi.

inputs: none
outputs: test type (integer), initial/ mean incidence, final incidence/ amplitude, pitch rate/ frequency (all single precision), drive & laser fire waveforms (single precision arrays)

panel1.vi

Gets basic test information off the user.

inputs: none
outputs: test type (integer), initial/ mean incidence, final incidence/ amplitude, pitch rate/ frequency (all single precision).

panel2.vi

Calculates the basic incidence and pitch rate history.

inputs: test type (integer), initial/ mean incidence, final incidence/ amplitude, pitch rate/ frequency (all single precision).
outputs: incidence and pitch rate history (single precision arrays, angular unit in radians) and waveform update rate based upon 1050 points per waveform (single precision).

panel3.vi

From the pitch rate information the voltage values in the motor drive waveform are determined.

inputs: incidence and pitch rate history arrays (single precision arrays, angular unit in radians), and flange nut velocity to voltage conversion value (single precision).
outputs: motor drive voltage waveform (single precision array).

enable laser.vi

This vi presents the user with an option for firing the YAG laser.

inputs: none

outputs: laser enable status (boolean).

YAGFIRE.vi

This vi obtains the laser fire incidence from the user.

inputs: test type (integer), initial & final alpha (single precision).
outputs: incidence at which laser is to fire (single precision).

firetime.vi

Determines the time at which the YAG laser is to pulse.

inputs: test type (integer), incidence history (single precison array), incidence at laser pulse and drive waveform update rate (both single precision).
outputs: time to fire (single precision) and drive waveform array index at which laser is pulsed (integer).

synchro.vi

This vi adjusts the drive waveform to synchronize it with the laser flash lamp, and generates the laser fire and camera shutter control waveform.

inputs: motor drive voltage waveform and incidence (single precision arrays) time to fire and waveform update rate (single precision).
outputs: updated motor drive waveform and incidence history, and camera shutter and laser fire control waveform (single precision arrays)

set start.vi

This runs a static test with a 0^o initial incidence.

inputs: initial incidence for test.
outputs: none.

actuate.vi

This vi manages synchronization of the waveform generation with the YAG flash lamp (if necessary) and starts the model motion. The rate generator is set to the required value (update rate), synchronization is set if necessary (i.e. counter 1 is set to count down), and the motor drive and laser/ camera control waveforms are loaded into the modified DAQ vi AO Ext Waveform Gen.vi. If the test is sinusoidal the run parameters for this vi are altered accordingly so that the waveform is generated continuously rather than just once.

inputs: motor drive and camera/ laser control waveforms (single precision arrays) and update rate (single precision).